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THE NEXT ATOMIC AGE

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photographs by DAN WINTERS

ENERGY STAR Only the tip of the 35-ft.-high Advanced Test Reactor extends above the floor at the Idaho National Laboratory. The machine tests the durability of materials for next-generation designs by bombarding them with a quadrillion neutrons per square centimeter per second.

LEANING OVER THE RAIL of the metal catwalk, I peer down through 16 ft. of crystal-clear water at the cool, blue glow coming from the shapes at the bottom: partially spent uranium fuel rods. "Blue," says Joel Duling, my guide to America's most sophisticated nuclear test reactor, "not green like on *The Simpsons*." The narrow canal snakes under the catwalk and makes a dogleg through an opening in the wall into the reactor area, a cavernous room that feels like a jet hangar. The top of the Advanced Test Reactor (ATR) pokes unobtrusively above the concrete floor. Most of the 35-ft.-high steel cylinder housing the reactor core lies underground. The chain reaction occurring there produces 250 megawatts—enough to power 201,000 homes. But, the ATR does something more important than generate energy. The machine tests fuels and alloys against the extreme conditions expected in exotic new reactors—radical designs that could produce power in molten salt, snap together like LEGOs and operate without water, safely and affordably fulfilling the decades-old dream of clean, abundant nuclear power.

The test reactor, part of the Department of Energy's (DOE) Idaho National Laboratory (INL), sits on an 890-square-mile tract of land known simply as "The Site." Located 45 minutes from Idaho Falls in the southeastern corner of the state, this swath of windswept desert is the epicenter of American nuclear energy research. Over the past half century, 51 reactors have been built here, including first-generation prototypes of the 1950s; only three still operate.

But it is among the relics of these early experiments that the country's energy future is taking shape.

In recent years, the debate over nuclear power has moved to the front burner, spurred by concerns about foreign oil and the specter of global warming. But what many on both sides of the issue often fail to note is that America's 103 existing nuclear reactors are aging. Over the next few decades, they will have to be decommissioned—taking 20 percent of the country's electrical supply with them.

In the Energy Policy Act of 2005, Congress approved up to $2.95 billion in incentives for new nuclear plants, and set aside another $1.25 billion for an experimental reactor to be built here in the Idaho desert. The reactor will be the centerpiece of a modern-day Manhattan Project, with scientists from around the world working together to revolutionize the production of nuclear power.

NUCLEAR SHORTCUT

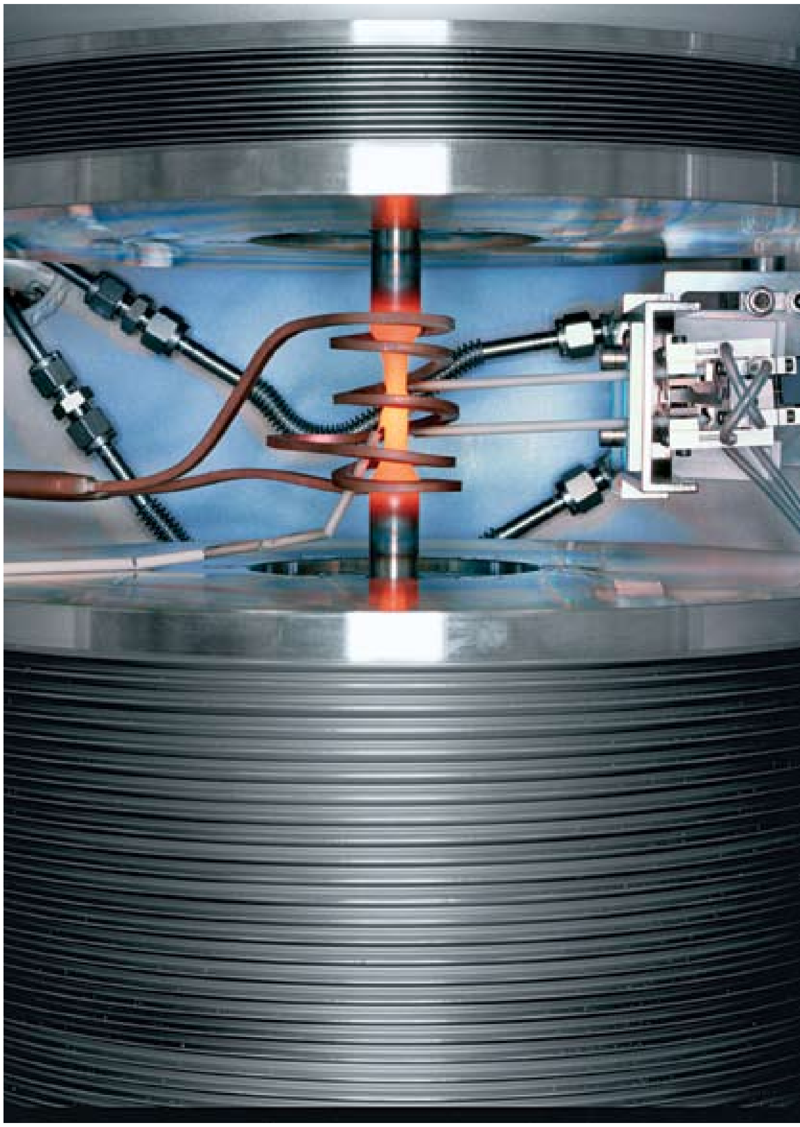
AT THE HEART OF EVERY reactor is fuel—usually uranium—undergoing a chain reaction that generates heat and fast-moving neutrons. A coolant draws away the heat and uses it to spin a turbine to generate electricity, and a moderator slows the neutrons to keep the reaction under control. Any material used in building a reactor has to withstand the heat—as well as intense pressure and a constant barrage of neutrons—for the reactor's projected lifetime. To prove that a new alloy can last 25 years, you could put it in a furnace for 25 years and bombard it with neutrons—or, if you don't want to wait that long, you can use the ATR.

"It is like a time machine," says Duling, the facility's former deputy director. The reactor uses uranium enriched to 92 percent (anything more than 20 percent is considered weapons-grade) to generate a quadrillion neutrons per square centimeter per second—100 to 1000 times greater than commercial reactors. By cranking up the neutron dose, the ATR can simulate as much as 40 years of wear and tear on a new fuel or alloy in a single year.

The test reactor is a simple water-cooled model built in 1967. But by tuning the pressure, temperature and chemistry inside its core, scientists can use it to reproduce the conditions in just about any other type of reactor. Recently, they tested chunks of graphite to see whether it's safe to extend the life of Britain's antiquated Magnox reactors. INL staff are now gearing up for an even bigger challenge: testing parts for proposed Generation IV reactors, which would leap technologically two steps ahead of the Gen II designs operating commercially in the United States today.

Despite concerns about catastrophic accidents and radioactive waste disposal, Gen II plants "are cost-effective and working well, and safety continues to improve," says James Lake, INL's associate director. Yet, no new reactors have been ordered in the States since the industry's peak sales year of 1973. Simple economics quashed further growth.A typical 1000-megawatt reactor costs up to $2 billion—2.5 times more than a comparable natural gas plant.

Thanks to the 2005 congressional incentives, a dozen utilities around the country have once again started the lengthy process of applying to build nuclear plants. If all goes smoothly, they could produce power by the middle of the next decade. These reactors would be Generation III and III+ designs—evolutionary improvements on today's Generation II reactors, which use water in some form as both a coolant and a moderator.



CORE SCIENTISTS Joel Duling (below left), former deputy director of the Idaho National Laboratory, and materials specialist Kevan Weaver. Opposite: Testing "creep fatigue" at 1832 F in an alloy intended for use in an exotic new reactor.

But, according to the DOE, what is really needed are even safer, cheaper reactors that produce less waste and use fuel that's not easily adapted for weapons production. To develop this kind of reactor, 10 countries, including the United States, joined forces in 2000 to launch the Generation IV International Forum. A committee of 100-plus scientists from participating countries evaluated more than 100 designs; after two years, they picked the six best. All of the final Gen IV concepts make a clean break from past designs. Some don't use a moderator, for instance. Others call for helium or molten lead to be used as coolants.

PEBBLE POWER

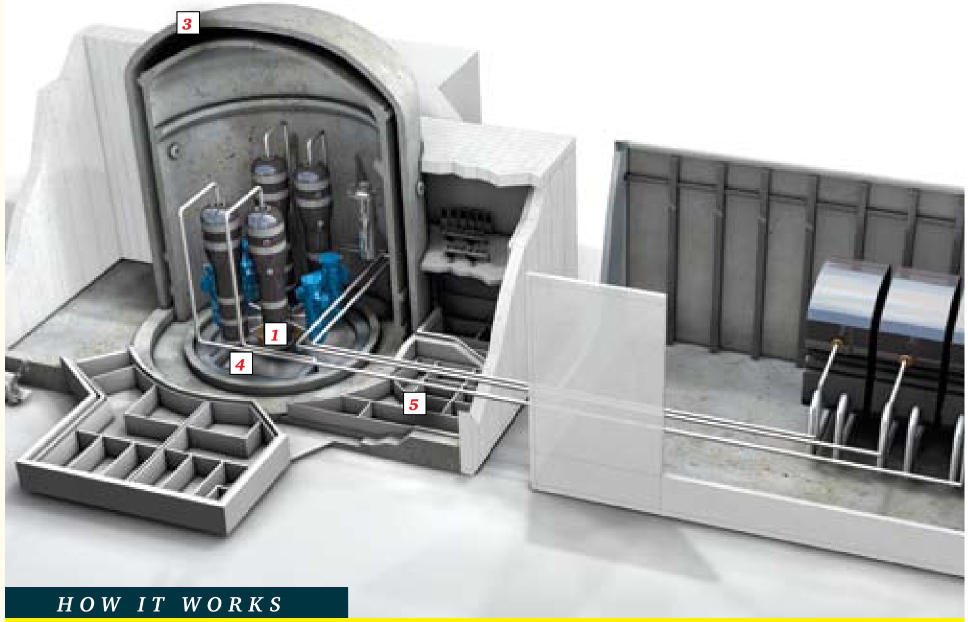
KEVAN WEAVER, like most of the lab's 3500 employees, works in a sprawling group of campus-like buildings on the outskirts of Idaho Falls. Standing in his third-floor office, the fresh-faced nuclear engineer holds what could be the future of nuclear power in his hand: a smooth graphite sphere about the size of a tennis ball. It could take years to weigh the pros and cons of all six Gen IV designs, Weaver says, but Congress can't wait that long. In addition to replacing the aging fleet of Generation II reactors, the government wants to make progress on another front: the production of hydrogen, to fuel the dream of exhaust-free cars running independent of foreign oil.

As a result, the frontrunner for the initial $1.25 billion demonstration plant in Idaho is a helium-cooled, graphite-moderated reactor whose extremely high outlet temperature (1650 to 1830 F) would be ideal for efficiently producing hydrogen. There are a couple of designs that could run that hot, but the "pebble bed," so named for the fuel pebble that Weaver holds, is attracting particularly intense interest.

A typical pebble-bed reactor would function somewhat like a giant gumball machine. The design calls for a core filled with about 360,000 of these fuel pebbles—"kernels" of uranium oxide wrapped in two layers of silicon carbide and one layer of pyrolytic carbon, and embedded in a graphite shell. Each day about 3000 pebbles are removed from the bottom as fuel becomes spent. Fresh pebbles are added to the top, eliminating the need to shut down the reactor for refueling. Helium gas flows through the spaces between the spheres, carrying away the heat of the reacting fuel. This hot gas—which is inert, so a leak wouldn't be radioactive—can then be used to spin a turbine to generate electricity, or serve more exotic uses such as produce hydrogen, refine shale oil or desalinate water.

The pebbles are fireproof and almost impossible to use for weapons production. The spent fuel is easy to transport and store, though there still remains the long-term problem of where to store it. And the design of the nuclear reactor is inherently meltdown-proof. If the fuel gets too hot, it begins absorbing neutrons, shutting down the chain reaction. In 2004, the cooling gas and secondary safety controls were shut off at an experimental pebble-bed reactor in China—and

In a Gen II Pressurized Water Reactor, water circulates through the core ***[1]*** where it is heated by the fuel's chain reaction. The hot water is then piped to a steam generator, and the steam spins a turbine ***[2]*** that produces electricity. The Gen III Evolutionary Pressurized Reactor improves upon this design primarily by enhancing safety features. Two separate 51-in.-thick concrete walls ***[3]***, the inner one lined with metal, are each strong enough to withstand the impact of a heavy commercial airplane. The reactor vessel sits on a 20-ft. slab of concrete with a leaktight "core catcher," ***[4]*** where the molten core would collect and cool in the event of a meltdown. There are also four safeguard buildings ***[5]*** with independent pressurizers and steam generators, each capable of providing emergency cooling of the reactor core.



HOW IT WORKS

Generation II and III Reactors

All 103 nuclear power plants now operating in the United States employ light-water reactors, which use ordinary water as both a moderator and a coolant. The next wave of nuclear plants has taken these Generation II concepts to the next level, improving both safety and efficiency. Utilities plan to begin building Generation III reactors by the end of the decade.

ILLUSTRATIONS BY TRANSLUSZENT.DE

no calamity followed, says MIT professor Andrew Kadak, who witnessed the test.

Pebble-bed reactors also could be far more cost-effective than Gen II plants, which had an average construction time of more than nine years. Even proposed Gen III designs have an estimated build time of more than five years. Kadak's group at MIT has developed a pebble-bed design in which every part is small and light enough to be shipped by train and truck, so the components could be mass-produced off-site.

"Our whole approach is that you don't construct a reactor, you assemble it," Kadak says. "Think about LEGOs: You just clip them together." This could shorten construction time to as little as two years; if a part breaks, the module containing it could be replaced quickly. Kadak envisions small 250-megawatt reactors, with additional units added to meet demand, making the initial cost lower than that of current 1000-megawatt giants.

Starting next year, both China and South Africa intend to build full-scale prototype pebble beds based on a design developed in Germany in the 1960s. However, the concept being considered in Idaho will produce hotter gas. "The Chinese and South African reactors will be close to 1550 F," says Weaver, who is coordinating the pebble-bed program in Idaho, "and we want 1650 to 1830 F. Those100 degrees can make a huge difference." The extra heat will run the electricity-generating turbines more efficiently, and—crucially—meet the threshold for efficiently generating hydrogen from water.

Hydrogen is currently produced from natural gas by a process called steam reformation, which releases 74 million tons of heat-trapping carbon dioxide into the atmosphere each year. As a cleaner alternative, researchers are trying to figure out the best way to split the H from H_2O. A team at Idaho National Lab recently showed that electrolysis—using electricity to split the water molecule—is nearly twice as efficient at the high temperatures made possible by a pebble-bed reactor.

FAST BREEDERS

THOUGH THE pebble-bed reactor is promising, other Gen IV designs have distinct advantages, too. Three of the six under consideration are fast neutron reactors; the term refers to the high speed of the neutrons ricocheting around the reactor core when there is no moderator to slow them down. When fast neutrons collide with fuel particles, they can actually generate more fuel than they burn. Such breeder reactors were developed in the late 1940s, but remained more expensive than other designs. These reactors have more appeal today because they also can burn up the longest-lived radioactive isotopes in their fuel, producing waste that stays dangerous for hundreds of years instead of hundreds of thousands.

These fast reactor concepts differ in the material they use to cool the reactor core. One uses gas, another sodium, and the third, molten lead. But, so far, all three designs are still more expensive and further from completion than the other top contenders. One solution, Weaver says, would

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be to carry two different designs forward: "a thermal reactor like the pebble bed for the near term, and a fast reactor for the far term."

"Near term" is relative: Last year's Energy Policy Act doesn't require a final decision on construction of the demonstration plant until 2014, a cautious timeline that frustrates the program's boosters. In the meantime, research is pressing on in the Idaho desert and in Idaho Falls, where the Thursday night entertainment is the monthly dinner meeting of the nation's largest chapter of the American Nuclear Society. In the parking lot, bumper stickers read, "Split an atom, save a tree." **PM**

HOW IT WORKS

Generation IV Reactors

Fourth-generation nuclear power plants differ radically from current reactors by replacing water coolants and moderators, reaching higher temperatures, and gaining the potential to create hydrogen, as well as electricity.

One of the six Gen IV designs under consideration is the meltdown-proof pebble-bed reactor, which uses grains of uranium encased in balls of graphite as fuel. Helium gas is heated as it circulates through a vessel of these pebbles ***[1]*** and then powers a turbine ***[2]*** to generate electricity. A heat exchanger ***[3]*** can transfer heat from the helium to adjacent facilities ***[4]*** for the production of hydrogen. The plant relies on "passive safety": If the cooling system fails, the nuclear reaction grinds to a halt on its own.